REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
9/30/97

3. REPORT TYPE AND DATES COVERED
FINAL

4. TITLE AND SUBTITLE
ADVANCED ARRAY PROCESSING FOR COMMUNICATIONS

5. FUNDING NUMBERS
DAAL03-91-C-0022

6. AUTHOR(S)
B. Friedlander

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Signal Processing Technology, Ltd.
450 San Antonio Rd., #57
Palo Alto, CA 94306

8. PERFORMING ORGANIZATION

19971204 088

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 27899.1-LS-S

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Reliable communications in the crowded and hostile environment of the future battlefield is a difficult and challenging problem. Array processing technology must be a key element in any system designed to face these challenges. In this project we addressed some of the open issues which need to be resolved for a successful transition of advanced array processing techniques from theory into practice. The problems we considered can be divided roughly into five categories: (i) Array Processing in a Multipath Environment; (ii) Array Calibration; (iii) Diversely Polarized Arrays; (iv) Blind Array Processing; and (v) Array Processing for Broadband Signals. The report summarizes the key results obtained in this project, and provides a detailed bibliography listing over 100 publications prepared during this project.

14. SUBJECT TERMS
Digital Communication, Antenna Array, Multipath, Calibration, Polarization, Equalization

15. NUMBER OF PAGES
19

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Contents

1 Introduction

This final report summarizes work performed under an Army Research Office contract DAAL03–91–C–0022 titled "Advanced Array Processing for Communications," during the period from 15 April, 1991 to 30 September, 1997. This work was a continuation and extension of work performed by the principal investigator under previous contracts with the Army Research Office (contracts DAAL03–86–C–0018 and DAAL03–89–C–0007).

The research results obtained in the course of this project have been documented in 110 publications in professional journals and conference proceedings, listed in section 4, and will not be repeated here. The purpose of this report is to describe the problems addressed in this project (section 2) and to present a brief summary of the main results (section 3).

2 Statement of Problem

Reliable communications in the crowded and hostile environment of the future battlefield is a difficult and challenging problem. Array processing technology must be a key element in any system designed to face these challenges. While some of the technologies needed for operating in this difficult environment, such as spread spectrum communications and advanced modulation and coding techniques, are fairly mature and well developed, array processing is a relatively new technology and its potential for providing significant gains in system performance has not been fully realized yet. Research and development efforts in the area of array processing are, therefore, expected to have relatively high payoff during the next decade.

While advanced array processing techniques have been discussed in the literature for quite some time, the practical implementation of these techniques was at an early stage of development when this contract started. Various experimental systems using techniques such as MUSIC have been in existence, but as far as we know, there were no fielded systems employing high-resolution array processing algorithms at the time.

In this project we addressed some of the open issues which need to be resolved for a successful transition of advanced array processing techniques from theory into practice. This plan was based on the experience and insight gained during the earlier phases of this project, and from our interactions with members of the U.S. Army Signal Warfare Center.

The problems we considered can be divided roughly into five categories, which are briefly described below.

1. Array Processing in a Multipath Environment.
   The presence of multipath is a major obstacle to the proper operation of array processing systems. Understanding the ways in which multipath affects

the performance of the array, and developing processing techniques for optimizing performance in the presence of multipath, are central to the successful deployment of system utilizing antenna arrays.

2. Array Calibration.
   Advanced array processing techniques require precise calibration of the array. We have studied in detail the sensitivity of direction finding and signal COPY to calibration errors. We have also investigated techniques for calibrating the array on-line and off-line.

3. Diversely Polarized Arrays.
   Diversity is a key concept in communications, including for example frequency diversity and time diversity. Antenna arrays can provide a special form of diversity by using antennas with different polarization. We have investigated ways in which polarization diversity can be best used, and studied the performance advantages it offers.

4. Blind Array Processing.
   Array processing techniques usually require detailed knowledge of the array response. In some situations, such as severe, rapidly changing multipath, it is impractical or impossible to measure or estimate the array response. So-called "blind" array processing techniques attempt to separate multiple co-channel signals without assuming any knowledge of the array response. We have studied and developed various blind signal separation techniques and evaluated their performance.

5. Array Processing for Broadband Signals.
   Most array processing applications by far involve narrowband signals, i.e. signals whose bandwidth is small compared to its center frequency. In some applications, such as certain spread spectrum systems, underwater communications, etc., the narrowband assumption no longer holds. We have studied techniques for performing direction finding and signal COPY for broadband signals.

3 Summary of Main Results

3.1 Array Processing in a Multipath Environment

We have developed a number of direction finding algorithms capable of operating in the presence of high levels of signal correlation, which are often caused by multipath propagation. The interpolated array approach which we developed appears to be a very promising approach to the multipath problem [9, 13, 14, 15, 31, 59, 60, 64, 82, 100, 102]. Since its development, the interpolated array has been widely used by other researchers.

An important collection of results has been produced in this project on the performance analysis of direction finding and signal COPY algorithm. In a series of papers we carried out a detailed performance analysis for each of these algorithms [1, 3, 5, 10, 11, 17, 18, 19, 22, 24, 25, 37, 56, 61, 65, 67, 68, 72, 73, 74, 85, 88, 98, 102, 104, 105]. Closed form expressions for the covariance matrix of the DOA estimation errors were derived using a perturbation analysis. Evaluating these expressions for specific cases and comparing them to the Cramer Rao lower bound for the DOA estimates, provides insight into the statistical efficiency of these algorithms. The formulas for the error covariance are quite general, and can be specialized to provide results for other DOA estimation algorithms as well.

We have also developed the basic theory for arrays whose elements are located on several platforms, and may be moving relative to each other. Consider for example a DF system which combines a small fixed array and an small vehicle-mounted array. If the vehicle is stationary, we have a static (time-invariant) array whose properties are well understood. It is interesting to consider, however, what happens if the vehicle is in motion: does the resulting time-varying array have any performance advantages over the static array? Our study seems to indicate that time-varying arrays have potential advantages over time-invariant arrays of comparable dimensions. They are more robust to ambiguity errors, and to the presence of correlation between the sources. In a series of papers we quantified these advantages by developing bounds on the accuracy of direction estimation using time varying arrays. We have also developed computationally efficient estimation algorithms based on eigen-decomposition techniques for time-varying arrays [33, 35, 38, 42, 76, 79, 84, 91, 105].

3.2 Array Calibration

A focal point for our research has been the question: how to apply advanced high-resolution array processing techniques in the presence of various uncertainties in the array parameters. These uncertainties can take on many different forms: imprecisely known location of the array elements, unknown variations in the gain and phase of individual elements, and other deviations between the model on which these techniques are based, and reality.

The problem outlined above is of great practical importance. The accurate calibration of the array, required in order to apply "standard" high-resolution techniques, is very costly. Furthermore, in many situations it is practically impossible to maintain the array calibration. Consider for example a mobile communication antenna array which needs to be dismantled and reassembled in the field, its calibration changing each time it is moved. Or consider a conformal array mounted on the wing of an aircraft, where mechanical vibrations constantly change the shape of the array.

To address these problems, which are a major deterrent to the practical application of these promising high-resolution techniques, we have developed a number of techniques to self calibrate the array using "signals-of-opportunity". We were able to

show that it is possible to simultaneously estimate unknown source locations and the unknown array parameters, under some reasonable assumptions. It is important to note that this self-calibration procedure does not require that we know the directions of the calibrating sources.

More recently, we performed an extensive sensitivity analysis of direction finding techniques based on the covariance matrix of the received signals. Using the results of this analysis we can now quantify the effect of various types of calibration errors on the accuracy of the direction-of-arrival estimates, and on the ability of the array to resolve closely spaced sources.

Our work on the sensitivity issue and the self-calibration problem appears to be the first systematic attempt to analyze and improve the robustness of high-resolution direction finding techniques in the presence of various system errors. The publication of our key results [4, 12, 18, 23, 26, 27, 40, 45, 51, 54, 66, 75, 92, 99] seems to have stimulated an intensive research activity in this area as evidenced by papers published in recent years.

3.3 Diversely Polarized Arrays

An important part of our work focused on the exploitation of polarization diversity for direction finding problems. We were able to develop a number of computationally efficient algorithms for the simultaneous estimation of the direction of arrival and polarization parameters of multiple signals. By studying the performance of these techniques we were able to quantify the advantages of utilizing polarization diversity for both uncorrelated and correlated sources. It is quite clear from our studies that polarization diverse systems should be preferred in future direction systems. Such systems are not significantly more complex than systems which do not use polarization diversity, but are capable of improved performance if the signals of interest have different polarization characteristics. As expected, when the signals of interest have identical polarizations, the performance of a polarization diverse array is essentially the same as that of a corresponding uniformly polarized array. These results are summarized in [3, 10, 17, 19, 22, 24, 27, 28, 45, 61, 65, 67, 68, 72, 73].

3.4 Blind Array Processing

Our recent research has focused on the problems associated with using "smart" antenna arrays for mobile communications networks. Such antenna arrays are expected to play an increasingly important role in the future, since they make it possible to increase the capacity of the system, without requiring the allocation of more frequency channels. This increased capacity can be achieved by using directional antenna arrays which are able to separate multiple transmissions in the same frequency band, based on the fact that different transmitters are located in different directions relative to the receiver. In other words, each node in the network will need to be equipped

with a small mobile antenna array, and the associated receivers and signal processing hardware. Using this equipment it will be able to discriminate between different transmission based on their direction, as well as their frequency.

To make such a system work, it is necessary to develop algorithms which are able to take the mixture of signals received by the elements of the array, and separate them into their individual components. This must be done quickly and reliably, in the presence of rapidly changing propagation conditions. Conventional techniques for signal separation require detailed knowledge of the array response, i.e., of the voltages measured at the outputs of the different antennas, when it receives a transmission from a given direction. In many situations, especially in an urban environment, these transmissions undergo reflections from buildings, vehicles, or the terrain. (These reflections are referred to collectively as "multipath"). Thus, the array response to a given transmitter is unpredictable and unknown to the receiver. Consequently, conventional array processing techniques fail to properly separate signals in this environment.

Our work has focused on the development of signal separation techniques which do not require knowledge of the array response. Such techniques are commonly referred to as "blind" estimation technique. To accomplish the seemingly impossible task of separating the signals without any knowledge of the array behavior, these techniques rely on some fundamental properties of the signals themselves. For example, it is reasonable to assume that signals arriving from different transmitters would be statistically independent. Thus, if we are able to decompose the mixture of signals received by the array, into a sum of independent components, we would have accomplished the task of separating the signals.

Various techniques for decomposing signals into independent components have been proposed in the past. These techniques are computationally intensive and involve calculations of high order statistics of the array outputs. A recent breakthrough in this area has been the development of computationally simple adaptive algorithms, by a group of French researchers. The computational simplicity of these algorithms, makes it possible for the first time, to consider their use in practical real-time applications. We are in the process of developing improved versions of these "blind" adaptive algorithms and analyzing their performance. So far all of our work has been theoretical. However, in the near future we intend to test our algorithms on recorded real array data.

We believe that with this new class of algorithms, it will be possible to design small mobile arrays which will be able to work in the challenging environment of the future battlefield. These arrays will offer an interference rejection capability (by separating the desired signal from the interfering one), and the ability to carry out multiple communication links on a single channel. These "smart" antenna arrays will provide a significant enhancement of military and commercial communication networks. It is worth noting that significant research efforts in this direction are being undertaken by companies who design commercial mobile cellular communications networks.

Our work so far, which has been primarily theoretical, has been used by other researchers who work on the signal separation problem. The next phase of our work is aimed at providing a proof-of-concept by testing these algorithms on real-data. We believe that a successful completion of this phase will be followed by a rapid transition of this technology to the Army, and various DOD agencies. Our work on blind array processing is summarized in [2, 6, 44, 46, 53, 80, 98, 103, 106].

3.5 Array Processing for Broadband Signals

Most of the work on advanced array processing treats the case of narrowband signals. Various extensions of MUSIC to the broadband case have been proposed in the literature, based mainly on the idea of focusing the outputs of a sensor array so that broadband signals can be represented by low rank models, prior to applying the conventional MUSIC algorithm. In coherent signal subspace methods, focusing matrices are used to align narrowband components within the receiver bandwidth prior to forming covariance matrix estimates at each frequency. The estimated narrowband covariance matrices are then averaged to obtain focused covariance matrix wherein each source has a rank one representation. The resulting focused matrix can be estimated with an accuracy which reflects the full time-bandwidth product of the sources. Although coherent signal-subspace methods offer a significant improvement in detection and resolution thresholds over incoherent methods, in "multi-group" scenarios where the sources are clustered around several widely separated directions, formation of the necessary focusing matrices has thus far required preliminary estimates of the source directions. In the multi-group case, preliminary source location estimates have been used to spatially whiten the field, thereby reducing it to the single group situation, or more recently, to form rotational subspace focusing matrices.

In this project we developed an approach to the focusing problem similar to the spatial resampling technique, but more general in that it can be applied to arbitrary array geometries. Furthermore, this technique has some computational advantages since it allows the use of the root-MUSIC algorithm. The technique is based on the idea of array interpolation and is described in [15, 60, 64]. We have also performed a detailed performance analysis of this method [15]. See also [52, 97] for some related work.

4 List of Publications

The following is the list of publications written during this project.

Journal Publications

[1] B. Friedlander and A. J. Weiss "Direction Finding in the Presence of Mutual Coupling," *IEEE Trans. Antennas and Propagation* vol. AP-39, No. 3, pp. 273–284, March 1991.

[2] B. Friedlander and B. Porat, "Blind Equalization of Digital Communications Channels Using High Order Moments," *IEEE Trans. Acoustics, Speech and Signal processing*, vol. 39, no. 2, pp. 522–526, February, 1991.

[3] A. J. Weiss and B. Friedlander, "Performance Analysis of Diversely Polarized Antenna Arrays," *IEEE Transactions on Acoustics, Speech and Signal Processing*, vol. ASSP-39, no. 7, pp. 1589–1603, July 1991.

[4] A. J. Weiss and B. Friedlander, "Array Shape Calibration via Eigenstructure Methods," *J. Signal Processing.* vol. 122, no. 3, pp. 251-258, 1991.

[5] B. Friedlander an A. J. Weiss, "On the Number of Signals Whose Directions Can Be Estimated by an Array," *IEEE Transactions on Acoustics, Speech and Signal Processing*, vol. ASSP-39, no. 7, pp. 1686–1689, July 1991.

[6] B. Porat and B. Friedlander, "Direction Finding Techniques Based on High Order Statistics," *IEEE Transactions on Signal Processing*, SP-39, No. 9, pp. 2016-2024, September 1991.

[7] B. Friedlander and B. Porat, "Performance Analysis of Transient Detectors Based on Linear Data Transforms," *IEEE Transaction on Information Theory*, vol. 38, no. 2, pp. 665-673, March, 1992.

[8] B. Porat and B. Friedlander, "Performance Analysis of a Class of Transient Detection Algorithms – A Unified Framework," *IEEE Transactions on Signal Processing*, vol. 40, no. 10, pp. 2536–2546, October, 1992.

[9] B. Friedlander and A. J. Weiss, "Direction Finding Using Spatial Smoothing with Interpolated Arrays," *IEEE Transactions on Aerospace Electronic Systems*, vol. 28, no. 2, pp. 574–587, April, 1992.

[10] B. Friedlander and A. J. Weiss, "Performance of Diversely Polarized Antenna Arrays for Correlated Signals," *IEEE Trans. Aerospace Electronic Systems*, pp. 869–879, vol. 28, no. 3, July, 1992.

[11] A. J. Weiss and B. Friedlander, "On the Cramer Rao Bound for Direction Finding of Correlated Signals," *IEEE Transactions on Signal Processing*, vol. 41, no. 1, pp. 495–499, January, 1993.

[12] B. Friedlander and A. J. Weiss, "Performance of Direction Finding Systems with Sensor Gain and Phase Uncertainties," *J. Computers, Systems and Signal Processing*, vol. 12, no. 1, pp. 3–35, 1993.

[13] A. J. Weiss and B. Friedlander, "Performance Analysis of Spatial Smoothing with Interpolated Array," *IEEE Trans. Signal Processing*, vol. 41, no. 5, pp 1881-1892, May 1993.

[14] B. Friedlander, "The Interpolated Root-MUSIC Algorithm for Direction Finding," *European J. Signal Processing*, vol. 30, pp. 15–29, 1993.

[15] B. Friedlander and A. J. Weiss, "Direction Finding for Wideband Signals Using an Interpolated Array," *IEEE Transactions on Signal Processing*, pp 1618-1634, April, 1993.

[16] B. Porat and B. Friedlander, "FIR System Identification Using Fourth Order Cumulants with Application to Channel Equalization," *IEEE Transactions on Automatic Control,* vol. 38, no. 9, pp. 1394-1398, September 1993.

[17] A. J. Weiss and B. Friedlander, "Direction Finding of Diversely Polarized Signals Using Polynomial Rooting," *IEEE Transactions on Signal Processing* vol. 41, no. 5, pp 1893-1905, May 1993.

[18] A. J. Weiss and B. Friedlander, "Mutual Coupling Effects on Phase-Only Direction Finding," *IEEE Transactions on Antennas and Propagation*, vol. 40, no. 5, pp. 535–541, May, 1992.

[19] B. Friedlander and A. J. Weiss, "A Direction Finding Algorithm for Diversely Polarized Arrays," *Digital Signal Processing – A Review Journal*, vol. 2, no. 3, pp. 123–134, July, 1992.

[20] B. Porat and B. Friedlander, "On the Generalized Likelihood Ratio Test for a Class of Nonlinear Detection Problems", *IEEE Transactions on Signal Processing*, vol. 41, no. 11, pp. 3186-3190, November 1993.

[21] A. J. Weiss and B. Friedlander, "Range and Bearing Estimation Using Polynomial Rooting ," *J. Ocean Engineering*, vol. 18, no.2, pp. 130-137, April 1993.

[22] B. Friedlander and A. J. Weiss, "Signal Estimation using Diversely Polarized Arrays – a Performance Analysis," *IEEE Transactions on Signal Processing*, pp. 2628–2638, August, 1993.

[23] B. Friedlander and A. J. Weiss, "Signal Estimation Using Arrays with Model Errors," *IEEE Transactions on Signal Processing*, pp. 147-155, January, 1994.

[24] A. J. Weiss and B. Friedlander, "Maximum Likelihood Signal Estimation for Polarization Sensitive Arrays," *IEEE Trans. Antennas and Propagation*, vol. 41, no. 7, pp. 918–925, July, 1993.

[25] A. J. Weiss and B. Friedlander, "Preprocessing for Direction Finding with Minimal Variance Degradation," *IEEE Transactions on Signal Processing*, vol. 42, no. 6, pp. 1478–1485, June 1994.

[26] A. J. Weiss and B. Friedlander, "Effects of Modeling Errors on the Resolution Threshold of the MUSIC Algorithm," *IEEE Transactions on Signal Processing*, vol. 42, no. 6, pp. 1519–1526, June 1994.

[27] B. Friedlander and A. J. Weiss, "The resolution Threshold of a Direction Finding Algorithm for Diversely Polarized Arrays," submitted *IEEE Transactions on Signal Processing*, vol. 42, no. 7, pp. 1719-1727, July 1994.

[28] A. J. Weiss and B. Friedlander, "Manifold Interpolation for Diversely Polarized Arrays," *IEE Proc. – Radar, Sonar, Navig.*, Vol. 141, No. 1, February 1994, pp. 19–24.

[29] B. Friedlander and B. Porat, "The Sensitivity of High-Order Parameter Estimation to Additive Gaussian Noise", Chapter 3 in *Higher Order Statistical Signal Processing*, Eds. B. Boashash, E. J. Powers, A. M. Zoubir, Halsted Press (an Imprint of John Wiley), pp. 89-111, 1995.

[30] L. L. Scharf and B. Friedlander, "Matched Subspace Detection," *IEEE Transactions on Signal Processing*, *IEEE Transactions on Signal Processing*, vol. 42, no. 8, pp. 2146–2157, August 1994.

[31] A. J. Weiss, B. Friedlander and P. Stoica, "Direction-of-Arrival Estimation using MODE with Interpolated Arrays," *IEEE Transactions on Signal Processing*, vol. 43, no. 1, pp 296–300, January 1995.

[32] B. Porat and B. Friedlander, "Performance Analysis of Cumulant-Based Detection of non-Gaussian Signals," *Journal of Adaptive Control and Signal Processing*, special issue on Adaptive Signal Processing and Higher Order Statistics, vol. 10, no. 2/3, pp. 99-112, March-June 1996

[33] A. Zeira and B. Friedlander, "Direction Finding with Time-Varying Arrays," *IEEE Transactions on Signal Processing*,vol. 43, no. 4, pp. 927–937, April 1995.

[34] J. Francos and B. Friedlander, "Bounds for Estimation of Multi-Component Signals with Random Amplitude and Deterministic Phase," *IEEE Transactions on Signal Processing*, vol. 43, no. 5, pp. 1161–1172, May 1995.

[35] A. Zeira and B. friedlander, "On the Performance of Direction Finding with Time Varying Arrays," *European Journal of Signal Processing.* vol. 43, pp. 133-147, 1995.

[36] B. Friedlander and J. Francos, "Estimation of Amplitude and Phase Parameters of Multi-Component Signals," *IEEE Transactions on Signal Processing*, vol. 43, no. 4, pp. 917–926, April 1995.

[37] B. Friedlander and A. J. Weiss "Direction Finding Using Noise Covariance Modeling," *IEEE Transactions on Signal Processing*, vol. 43, no.7, pp. 1557–1567, July 1995.

[38] B. Friedlander and A. Zeira, "Eigenstructure Based Algorithms for Direction Finding with Time Varying Arrays," *IEEE Transactions on Signal Processing*, vol. 32, no. 2, pp. 689–701, April 1996.

[39] J. Francos and B. Friedlander, "Bounds for Estimation of Complex Exponentials in Unknown Colored Noise," *IEEE Transactions on Signal Processing*, vol. 43, no. 9, pp. 2176–2185, September 1995.

[40] A. Weiss and B. Friedlander, "DOA and Steering Vector Estimation Using a Partially Calibrated Array ," *IEEE Transactions on Aerospace Electronic Systems*, vol. 32, no. 3, pp. 1047–1056, July 1996.

[41] B. Friedlander and A. Zeira, "Oversampled Gabor Representation for Transient Signals", *IEEE Transactions on Signal Processing*, vol. 43, no. 9, pp. 2088–2094, September, 1995.

[42] A. Zeira and B. Friedlander, "Direction of Arrival Estimation Using Parametric Signal Models," *IEEE Transactions on Signal Processing*, vol. 44, no. 2, pp. 339–350, February 1996.

[43] B. Friedlander and J. Francos, "An Estimation Algorithm for 2-D Polynomial Phase Signals," *IEEE Transactions on Image Processing*, Special Isuue on Non-linear Image Processing, vol. 5, no. 6, pp. 1084–1087, June 1996.

[44] A. Weiss and B. Friedlander, " "Almost Blind" Steering Vector Estimation Using Second Order Mmoments," *IEEE Transactions on Signal Processing*, vol. 44, no. 4, pp. 1024–1027, April 1996.

[45] A. Weiss and B. Friedlander, "Steering Vector and Signal Estimation for Uncalibrated Polarization Sensitive Arrays," *Digital Signal Processing – A Review Journal*, vol. 6, pp 37-50, 1996.

[46] A. Weiss and B. Friedlander, " "Almost Blind Signal Estimation using Second Order Moments," *IEE Proc. - Radar, Sonar, Navig.*, vol. 142, no. 5, pp. 213–217, October 1995.

[47] Boaz Porat and Benjamin Friedlander "Estimation of Frequency in the Presence of Nonrandom Interference," *IEEE Transactions on Signal Processing*, vol. 44, no. 3, pp. 640–651, March 1996.

[48] Boaz Porat and Benjamin Friedlander, "Asymptotic Statistical Analysis of the High-Order Ambiguity Function for Parameter Estimation of Polynomial-Phase Signals," *IEEE Transactions on Information Theory*, vol. 42, no. 3, pp. 995-1001, May 1996.

[49] B. Friedlander and J. Francos, "On the Accuracy of Estimating the Parameters of a Stationary Process," *IEEE Transactions on Information Theory*, vol. 42, no. 4, pp. 1202–1211, July 1996.

[50] B. Porat and B. Friedlander, "Blind Deconvolution of Polynomial-Phase Signals Using the High-Order Ambiguity Function," *Journal of Signal Processing*, Vol. 53, No. 2-3, pp. 149–163, September 1996.

[51] A. Weiss and B. Friedlander, "Comparison of Signal Estimation using Calibrated and Uncalibrated Arrays," *IEEE Trans. Aerospace Electronic Systems*, vol. 33, no. 1, pp. 241–249, January 1997.

[52] B. Friedlander and A. Zeira, "Detection of Broadband Signals in Frequency and Time Dispersive Channels," *IEEE Transactions on Signal Processing*, pp. 1613–1622, vol. 44, no. 7, July 1996.

[53] A. J. Weiss and B. Friedlander, "Array Processing Using Joint Diagonalization," *European Journal on Signal Processing*, vol. 50, pp. 205–222, 1996.

[54] B. Porat and B. Friedlander, "Accuracy Requirements in Off-Line Array Calibration," *IEEE Transactions on Signal Processing*, vol. 33, no. 2, pp. 545–556, April 1997.

[55] B. Friedlander and J. Francos, "Model Based Phase Unwrapping of 2-D Signals," *IEEE Transactions on Signal Processing*, vol. 44, no. 12, pp. 2999–3007, December 1996.

[56] A. J. Weiss and B. Friedlander, "Fading Effects on Antenna Arrays in Cellular Communications," *IEEE Transactions on Signal Processing*, vol. 45, no. 5, pp. 1109–1117.

[57] A. Weiss and B. Friedlander, "Simultaneous Signals in IFM Receivers", *IEE Proc. - Radar, Sonar, Navigation,* vol. 144, No.4, August 1997, pp. 181–185.

[58] A. Zeira and B. Friedlander, "Gabor Representation and Signal Detection," Chapter in Gabor book

Conference Publications

[59] A. J. Weiss and B. Friedlander, "Performance Analysis of Spatial Smoothing with Interpolated Array," Intl. Conference on Acoustics, Speech and Signal Processing, Toronto, Canada, May 1991.

[60] B. Friedlander and A. J. Weiss, "Direction Finding for Wideband Signals Using an Interpolated Array," 25th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, November 4 – 6, 1991.

[61] A. J. Weiss and B. Friedlander, "Direction Finding of Diversely Polarized Signals Using Polynomial Rooting," 25th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, November 4 – 6, 1991.

[62] B. Friedlander and B. Porat, "Performance Analysis of Transient Detectors Based on Linear Data Transforms," 25th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, November 4 – 6, 1991.

[63] B. Porat and B. Friedlander, "Performance Analysis of a Class of Transient Detection Algorithms – A Unified Framework," Intl. Conference on Acoustics, Speech and Signal Processing, San Francisco, CA, 1992.

[64] B. Friedlander and A. J. Weiss, "Direction Finding for Wideband Signals Using an Interpolated Array," Intl. Conference on Acoustics, Speech and Signal Processing, San Francisco, CA, 1992.

[65] B. Friedlander and A. J. Weiss, "Performance of Diversely Polarized Antenna Arrays for Correlated Signals," Intl. Conference on Acoustics, Speech and Signal Processing, San Francisco, CA, 1992.

[66] B. Friedlander, "On the Sensitivity of Covariance Based Direction Finding to Gain and Phase Perturbations," Intl. Conference on Acoustics, Speech and Signal Processing, San Francisco, CA, 1992.

[67] B. Friedlander and A. J. Weiss, "A Subspace Rooting Algorithm for Estimating Bearing and Polarization," 3rd Intl Symposium on Signal Processing and its applications August 16-21, 1992, Australia.

[68] B. Friedlander and A. J. Weiss, "Performance Analysis of Signal Estimation Using Polarization Sensitive Arrays," Sixth SSAP Workshop on Statistical Signal and Array Processing, October 7–9, 1992, Victoria, British Columbia, Canada.

[69] B. Friedlander and B. Porat, "On the Performance of Cumulant Based Detection of Non-Gaussian Signals," Sixth SSAP Workshop on Statistical Signal and Array Processing, October 7–9, 1992, Victoria, British Columbia, Canada.

[70] B. Porat and B. Friedlander, "The Sensitivity of High-Order Parameter Estimation to Additive Gaussian Noise," Conference on "High-Order Statistical Signal Processing with Application to Nonlinear, Non-Gaussian, Non-Stationary Signals and Systems," 22-23 August, 1992, Australia.

[71] B. Porat and B. Friedlander, "On the Generalized Likelihood Ratio Test for a Class of Detection Problems", 26th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, October 26 – 28, 1992.

[72] A. J. Weiss and B. Friedlander, "Array Manifold Interpolation for Diversely Polarized Arrays," 26th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, October 26 – 28, 1992.

[73] A. J. Weiss and B. Friedlander, "Maximum Likelihood Signal Estimation Using Polarized Arrays," 26th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, October 26 – 28, 1992.

[74] A. J. Weiss and B. Friedlander, "The Effects of Preprocessing on Direction of Arrival Estimation," Intl. Conference on Acoustics, Speech and Signal Processing, Minneapolis, MN, 1993.

[75] B. Friedlander and A. J. Weiss, "Effects of Model Errors on Signal Reconstruction Using A Sensor Array," Intl. Conference on Acoustics, Speech and Signal Processing, Minneapolis, MN, 1993.

[76] A. Zeira and B. Friedlander, "Performance Analysis and Algorithms for Time Varying Arrays," Underwater Acoustics Signal Processing Workshop, 6–8 October, 1993.

[77] L. L. Scharf and B. Friedlander, "Matched Subspace Detection" Underwater Acoustics Signal Processing Workshop, 6–8 October, 1993.

[78] L. L. Scharf and B. Friedlander, "Matched Subspace Detection" 27th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, November 1 – 3, 1993.

[79] B. Friedlander and A. Zeira, "Direction Finding with Time Varying Arrays" 27th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, November 1 – 3, 1993.

[80] B. Friedlander "Techniques for Blind Array Calibration" 27th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, November 1 – 3, 1993.

[81] B. Friedlander and J. Francos, "Estimation of Amplitude and Phase Parameters of Complex Signals" 27th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, November 1 – 3, 1993.

[82] A. J. Weiss, B. Friedlander and P. Stoica, "DOA Estimation using interpolated Arrays with MODE" 27th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, November 1 – 3, 1993.

[83] B. Friedlander and J. Francos, "On the Accuracy of Estimating the Parameters of a Stationary Process," 1994 IEEE International Symposium of Information Theory, 27 June -1 July, 1994, Technical University of Trondheim, Norway.

[84] B. Friedlander and A. Zeira, "Eigenstructure based algorithms for time varying arrays," Annual Meeting of the ASA, Special session on Synthetic Aperture Sonar MIT, June 6-10, 1994.

[85] B. Friedlander and A. Weiss, "Noise Covariance Modeling In Array Processing," Seventh Workshop on Statistical Signal and Array Processing Quebec City, 6/26-29/94.

[86] J. Francos and B. Friedlander, " Parametric Estimation of Multi-Component Signals with Random Amplitude and Deterministic Phase," Seventh Workshop on Statistical Signal and Array Processing Quebec City, 6/26-29/94.

[87] Boaz Porat and Benjamin Friedlander "Frequency Estimation in the Presence of Nonrandom Interference," IEEE Digital Signal Processing workshop, October 2-5, 1994, Yosemite Lodge, Yosemite National Park, CA.

[88] B. Friedlander and A. Weiss, "On Direction Finding with Unknown Noise Covariance," 28th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, October 30 – November 2, 1994.

[89] B. Friedlander and A. Zeira, "Oversampled Gabor Expansion into One-Sided Exponential Functions," 28th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, October 30 – November 2, 1994.

[90] Boaz Porat and Benjamin Friedlander, "Accuracy Analysis of Estimation Algorithms for Parameters of Multiple Polynomial Phase Signals", Intl. Conference on Acoustics, Speech and Signal Processing, Detroit, Michigan, 5/8-12/95.

[91] Ariela Zeira and Benjamin Friedlander, "Array Processing using Parametric Signal Models," Intl. Conference on Acoustics, Speech and Signal Processing, Detroit, Michigan, 5/8-12/95.

[92] A. Weiss, B. Friedlander and D. Feldman, "Analysis of Signal Estimation Using Uncalibrated Arrays," Intl. Conference on Acoustics, Speech and Signal Processing, Detroit, Michigan, 5/8-12/95.

[93] B. Friedlander and J.M. Francos, "The Polynomial Phase Difference Operator for Parametric Modeling of 2-D Nonhomogeneous Signals," 1995 Information Theory Symposium, Whistler BC.

[94] J. Francos and B. Friedlander, The Polynomial Phase Difference Operator for Modeling Nonhomogeneous images," 1995 Image Processing Conference.

[95] B. Porat and B. Friedlander, " Estimation of Polynomial Phase Signals Distorted by Linear Channels," 29th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, October 29 – November 1, 1995.

[96] B. Friedlander and J. Francos, "Model Based 2-D Phase Unwrapping," 29th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, October 29 – November 1, 1995.

[97] A. Zeira and B. Friedlander, "On Detecting Broadband Signals in Frequency and Time Dispersive Channels," 29th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, October 29 – November 1, 1995.

[98] A. Weiss and B. Friedlander, "Algorithm for Steering Vector Estimation Using Second Order Moments," 29th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, October 29 – November 1, 1995.

[99] B. Porat and B. Friedlander, "Accuracy Requirements in Off-Line Array Calibration," Intl. Conference on Acoustics, Speech and Signal Processing, Atlanta, Georgia, 7-10 May, 1996.

[100] A. Zeira and B. Friedlander, "Interpolated Array Minimum Variance Beamforming for Correlated Interference Rejection," Intl. Conference on Acoustics, Speech and Signal Processing, Atlanta, Georgia, 7-10 May, 1996.

[101] J. M. Francos and B. Friedlander, "The Polynomial Phase Differencing Algorithm for 2-D Phase Unwrapping: Performance Analysis," Intl. Conference on Acoustics, Speech and Signal Processing, Atlanta, Georgia, 7-10 May, 1996.

[102] A. Zeira and B. Friedlander, "Adaptive Beamforming using an interpolated array for correlated interference rejection," Underwater Acoustic Signal Processing Workshop, 11-13 October 1995, Alton-Jones Campus, Rhode Island.

[103] A. J. Weiss and B. Friedlander, "Direction Finding via Joint Diagonalization," 8th IEEE Signal Processing Workshop on Statistical Signal and Array Processing, June 24-26, Corfu, Greece.

[104] A. J. Weiss and B. Friedlander, "Performance of Antenna Arrays with Fading Signals", Proceedings of 30th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, USA, 4-6 Nov. 1996.

[105] A. Zeira and B. Friedlander, "Joint Direction Finding, Signal and Channel Response Estimation for a Polynomial Phase Signal in a Multipath Channel", Proceedings of 30th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, USA, 4-6 Nov. 1996.

[106] A. Zeira and B. Friedlander, "On Blind Signal Copy for Polynomial Phase Signals", Intl. Conference on Acoustics, Speech and Signal Processing, 1997.

[107] J. Francos and B. Friedlander, "Parameter Estimation of 2-D Moving-Average Random Fields: Algorithms and Bounds", Intl. Conference on Acoustics, Speech and Signal Processing, 1997.

[108] B. Porat and B. Friedlander, "Fractionally Spaced Signal Reconstructions Based on Maximum Likelihood," 1997 Workshop on Higher-Order Statistics.

[109] B. Friedlander, "On the Statistics of Eigenvectors of Sample Covariance Matrices," Proceedings of 31th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, USA, 2-5 Nov. 1997.

[110] A. J. Weiss and B. Friedlander, "CDMA Downlink Channel Estimation with Aperiodic Spreading," Proceedings of 31th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, USA, 2-5 Nov. 1997.

In Review

[111] J. M. Francos and B. Friedlander, "Two-Dimensional Polynomial Phase Signals: Parameter Estimation and Bounds."

[112] J. M. Francos and B. Friedlander, "Parameter Estimation of Two-Dimensional Moving Average Random Fields."

[113] J. Francos and B. Friedlander, "Parameter Estimation of 2-D Random Amplitude Polynomial Phase Signals."

[114] J. Francos and B. Friedlander, "Performance Analysis of the Two-Dimensional Polynomial Phase Differencing Algorithm."

[115] A. J. Weiss and B. Friedlander, "Synchronous DS-CDMA Downlink with Frequency Selective Fading."

[116] A. J. Weiss and B. Friedlander, "CDMA Downlink Channel Estimation with Aperiodic Spreading."

[117] B. Friedlander and A. J. Weiss, "On the Statistics of Eigenvectors of Sample Covariance Matrices."

5 List of Project Participants

- Dr. Benjamin Friedlander

- Dr. Boaz Porat
- Dr. Anthony J. Weiss
- Dr. Joseph M. Francos
- Dr. Ariela Zeira

6 Report of Inventions

None.